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Chapter 6

Nondestructive Tests in Highway Engineering

Gunawan Handayani

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Abstract

In highway engineering, one needs to know the information about the thickness and elastic modulus of each pavement layer. The thickness and elastic modulus of each pavement component then become input to elasticity analysis or finite element computation to calculate the service life of the highway. An application was Multichannel Analysis of Surface Waves (MASW) measurement on highway in North Jakarta. The measurement was carried out on highway traffic, because we were not allowed to stop traffic of one of the busiest roads in Jakarta. The street is heading to Tanjung Priok, the port of Jakarta. However, we acquired fairly good data by applying stacking method. The number of stacking was 10 (ten) to overcome traffic noise. After inversion, we came up with the result of MASW measurement of the pavement. The result of MASW measurement in terms of elastic modulus and thicknesses of pavement layer becomes important input of finite element analysis to compute fatigue damage of pavement components.

Keywords: Multichannel Analysis of Surface Waves, MASW, surface waves, pavement

1. Introduction

In highway engineering, it is required to know the information about the thicknesses of pavement components and values of elastic modulus of pavement components. It is preferred to have nondestructive methods than destructive method (drilling method). The nondestructive methods are quicker to carry out than the destructive methods. More importantly, the pavement is not disturbed, i.e., no holes are required to be patched. Surface waves are employed in this nondestructive method. The method utilizes surface waves to determine the thickness and shear wave velocity of each layer. This chapter describes the procedure and methodology of surface wave method using multichannel recording. This method is popularly known as Multichannel Analysis of Surface Waves (MASW). This chapter further discusses the application of MASW method to busy highway in Jakarta. The high traffic noise was overcome by a recording technique

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known as stacking technique. This technique added to the fact that surface wave has the largest amplitude than other body waves (P and S waves) [1] resulted in good field data.

2. Methodology

The nondestructive method employed here is carried out by means of generating seismic waves on the surface. If one generates an impulsive source at the surface, it propagates seismic body waves (direct, refracted, reflected, scattered, guided, and air waves) and seismic surface waves (fundamental, higher modes, and scattered). The frequency content of the impulsive signal is very wide from nearly zero Hz until infinite Hz as can be seen from Fast Fourier Transforms computation below (**Figure 1**):

The pavement structure has strong layer in the upper layer and softer layer underneath. In this situation, the Snell's law governs that the wave would be refracted down if it meets interface between strong layer and soft layer. This is the main reason, the body wave method, i.e., refraction method cannot be applied (**Figure 2**).

By hammer blow, one generates impulsive signal and propagates body waves and surface waves into the pavement system. If one sets up an array of receiver sensors, i.e., geophones or accelerometers, he acquires shot gather, which is a recorded time series file of receiver sensors. An example of shot gather is shown in **Figure 3**.

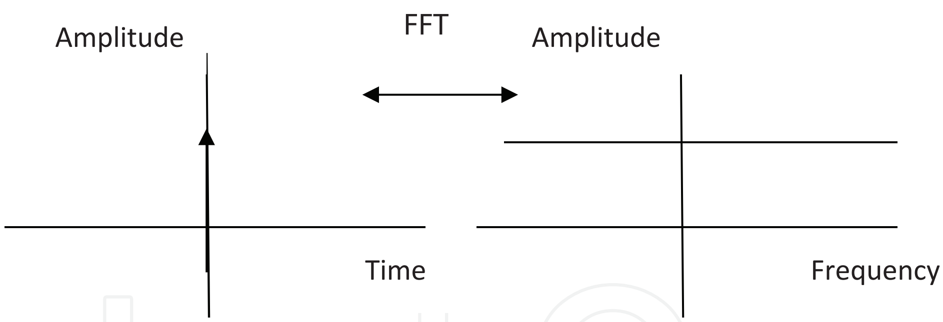

Figure 1. FFT relationship between time duration of a signal and its spectrum.

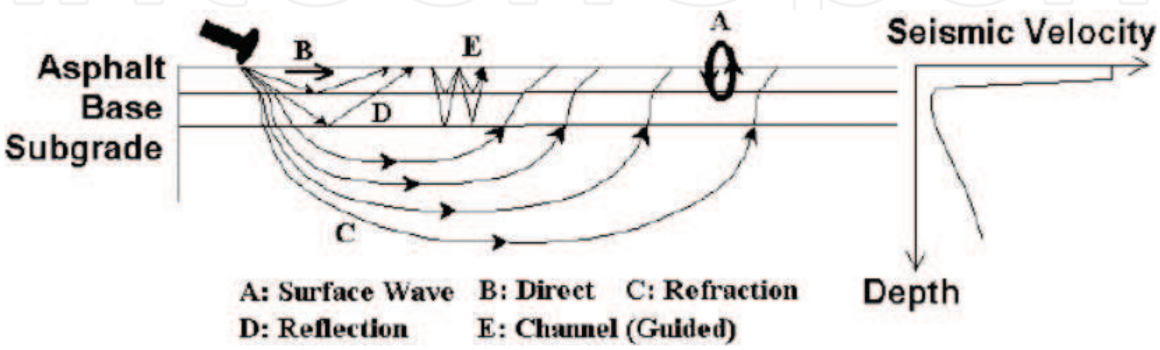

Figure 2. Generalized structure of an Asphalt system [2].

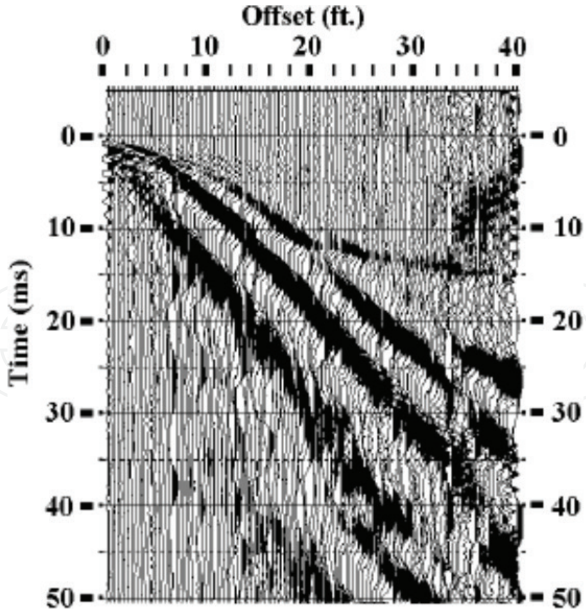

Figure 3. An example of shot gather obtained from hammer blow on the surface.

As it can be seen from the shot gather, the dominant event of arrival waves is surface waves, because their amplitude is very large compared to body waves (P or S waves). For the surface waves, people usually assume they contain fundamental mode. They actually contain higher modes too. However, up to now, the inversion algorithms usually ignore the higher modes. As hammer hit the surface, the surface waves propagate through the pavement system. The high frequency component (the small wavelength component) propagates through the upper thinnest pavement layer, whereas the lower frequency component (the larger wavelength) will propagate and vibrate through the deeper pavement layer. As the result of this process, there is velocity discrepancy between the high-frequency component, which travels with velocity of first layer, and lower frequency component, which travels with velocity of deeper layer (material). This velocity discrepancy is called dispersion, which means velocity as function of frequency (wavelength) (**Figure 4**) [3].

The shot gather from the hammer blow can be considered as time series:

$$f(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{2\pi nt}{T} + b_n \sin\frac{2\pi nt}{T}\right) \tag{1}$$

2.1. Forward modeling

If we have soil model on the left, the time series (shot gather) would be on the right (**Figures 5–7**):

The field records we acquired from the field then undergo data processing with the flow:

1. Compute Fast Fourier Transform (FFT) to the shot gather f(x, t):

$$F(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)\,.\,e^{-i\omega t}\,dt \tag{2}$$

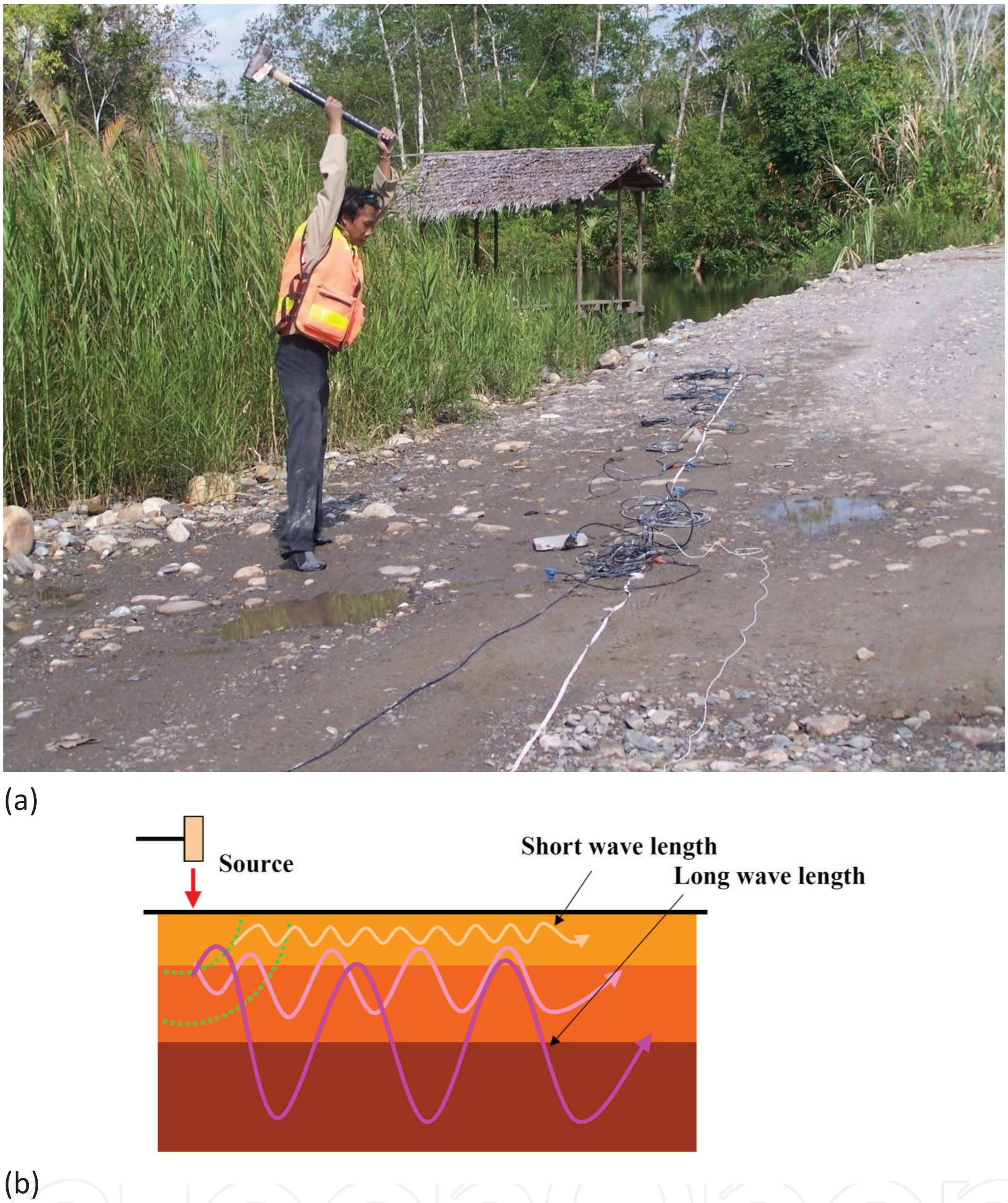

Figure 4. (a) Hammer blow as the source of energy. (b) Hammer blow would propagate many wavelength (frequencies).

and we obtain F(x, ω) record, and:

2. Redo the Fast Fourier Transform (FFT) to F(x, ω):

$$F(c, \omega) = \int_{-\infty}^{\infty} F(x, \omega) \, . \, e^{i\omega \frac{x}{c}} \, dx \tag{3}$$

where c = the phase velocity of the surface wave; ω = the angular frequency; x = distance of the sensor.

The whole process can be described in the following flow chart (**Figures 8–11**) [5]:

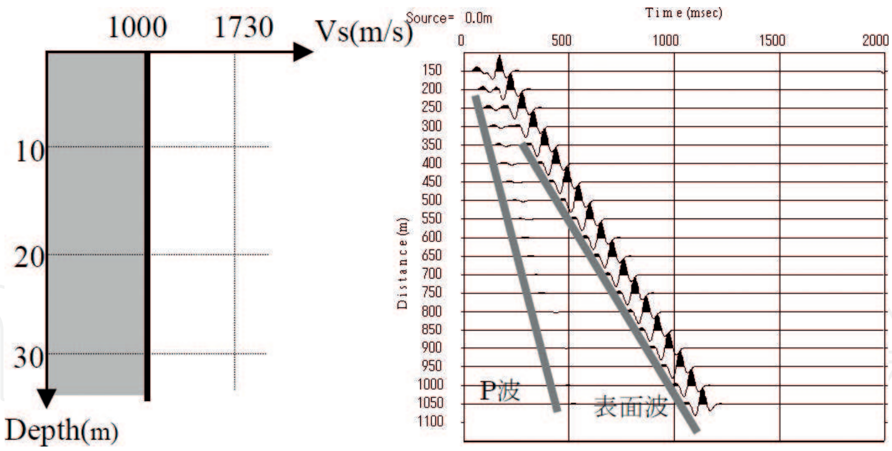

Figure 5. A soil model with velocity of 1000 m/s [4].

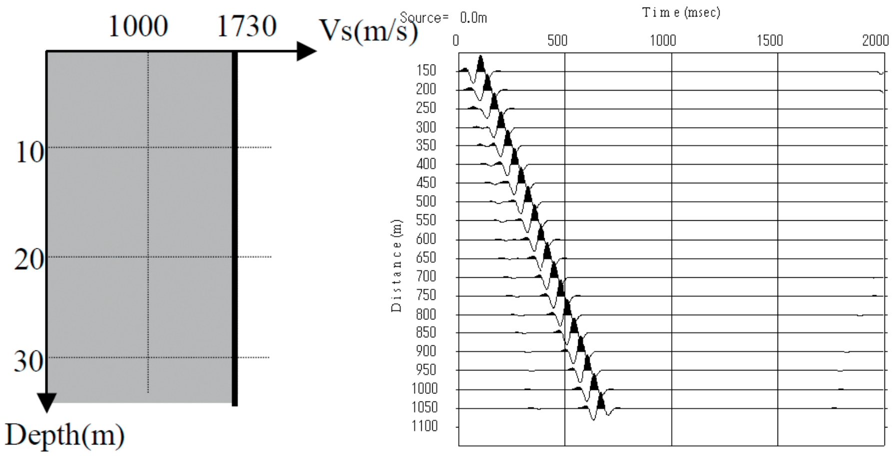

Figure 6. A soil model with velocity of 1730 m/s [4].

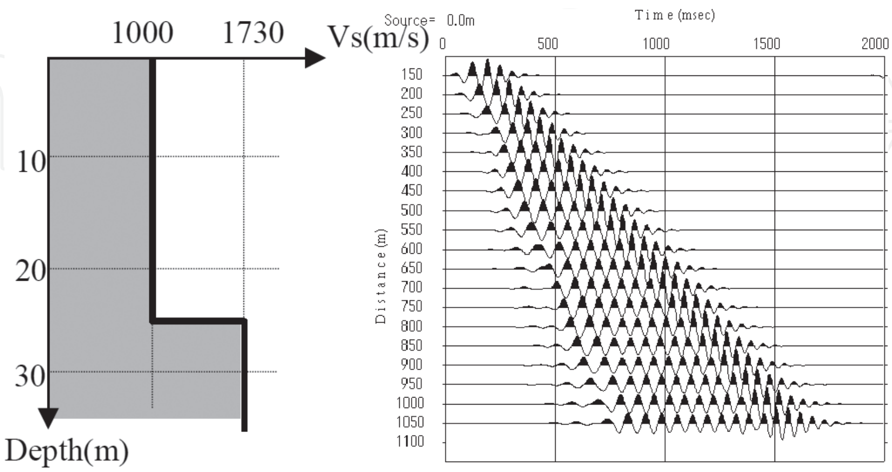

Figure 7. Combination of soil model with velocity of 1000 m/s and of 1730 m/s [4].

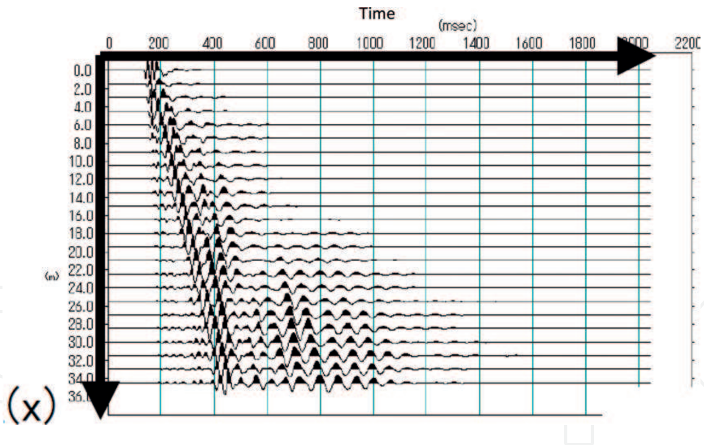

Figure 8. The shot gather.

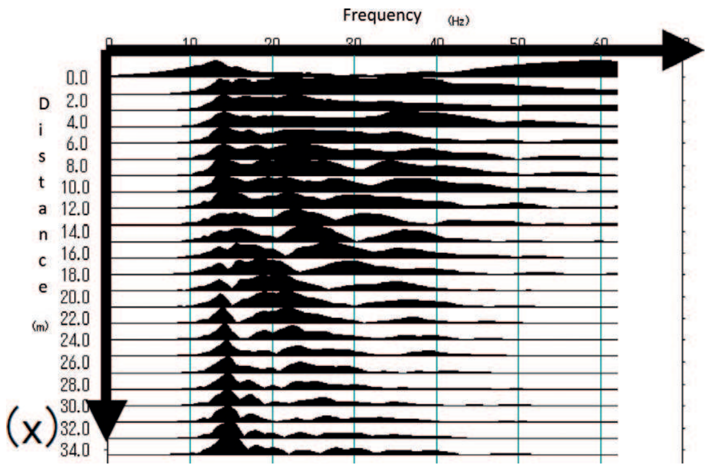

Figure 9. After FFT computation one obtains F(x, w).

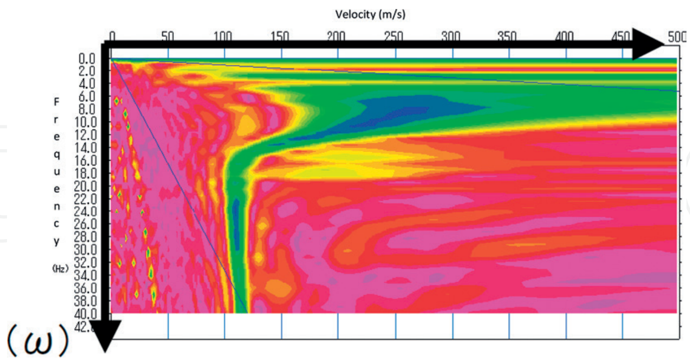

Figure 10. Finally one obtains spectrum velocity with respect to angular frequency F(c, ω) [4].

At this point, we analyze the waves, which are received by geophones from the spectrum F(c, ω), i.e.:

C: surface waves (fundamental mode).

B: surface wave (Higher mode).

A: body waves.

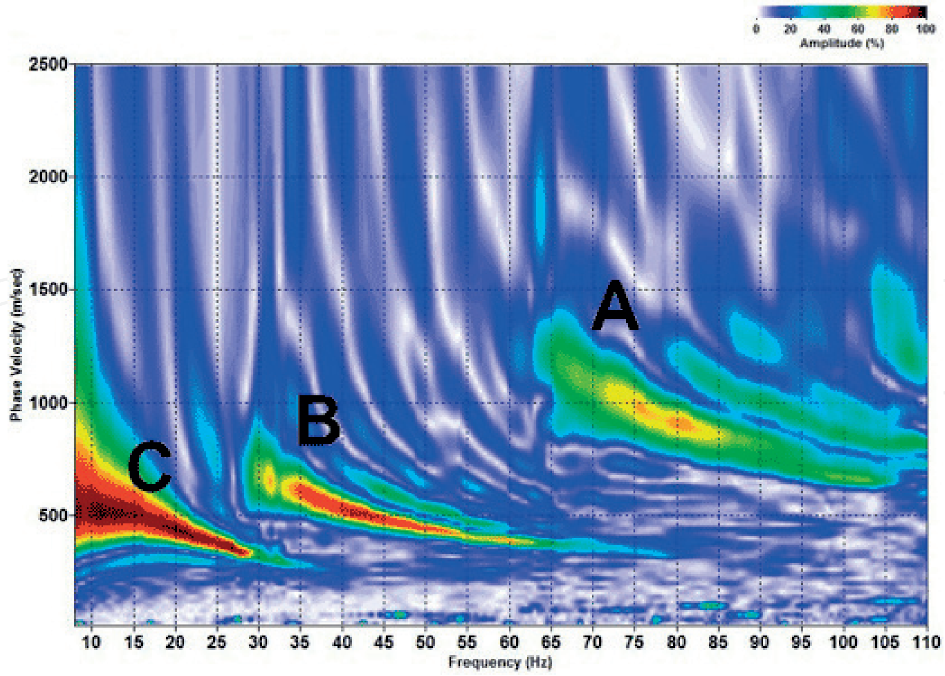

Figure 11. Pattern recognition of wave type in spectrum velocity with respect frequency [6].

For inversion purpose, we pick the surface wave (fundamental mode) only which is characterized by larger amplitude and lower velocity.

To record the surface waves, we employ geophones sitting on aluminum platform called land streamer, so there is no need to drill the surface of the pavement [7].

After picking the fundamental mode of the surface waves, one has the field dispersion curve to be inverted by utilizing commercial inversion program to come up with shear velocity profiles, i.e., velocity of shear wave with respect to depth. The inversion programs themselves are of many different kinds. We only focus on least square inversion program (**Figure 12**) [8].

2.2. The highway application

As an illustration of the process above, let us look at the real application, i.e., MASW (Multichannel Analysis of Surface Waves) measurement on the busy street in North Jakarta. The traffic was not allowed to be stopped, since it could disrupt the economic arteries of Jakarta and the street was heading to the Tanjung Priok, Jakarta's port. Therefore, we carried out the measurement side by side with busy traffic. The equipments employed are seismic data logger seistronix 24 bit, OYO geophones 4.5 Hz, and land streamer. The field parameters were (a) near offset (distance between the weight drop blows and the first geophone) was 18 m, (b) inter distance among geophones was 3 m, and (c) number of geophones was 12 geophones (**Figure 13**).

Even though a lot of street noise, we managed to acquire a fairly good data by applying stacking technique, which is basically we add up the records from the same source offset distance:

$$a_t = \frac{1}{N}\sum_{i=1}^{N} S_i \tag{4}$$

where S_i = amplitude of ith record; N = number of repetition; a_t = amplitude of stacked record.

Figure 12. A land streamer.

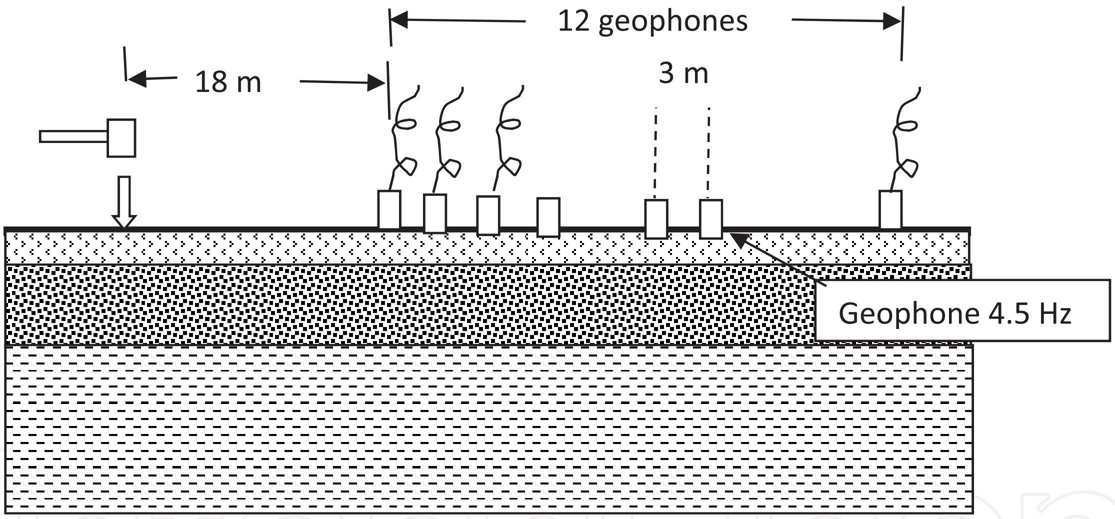

Figure 13. Field configuration of MASW measurement along with field measurement parameters [9].

Using this technique, random noise will add up to the same amplitude and after dividing it by number of repetition becomes one amplitude over number of repetition, whereas adding up coherence signal would result in number of repetition times original amplitude. After dividing it by number of repetition, we obtain initial amplitude. In this method, we suppress the traffic noise as one over number of repetition (**Figure 14**).

After stacking method, this shot gather was acquired as follows (**Figures 15** and **16**):

The FFT computation was carried out and resulted in spectrum F(c, ω) as follows (**Figure 17**):

Figure 14. MASW data acquisition using land streamer on busy street.

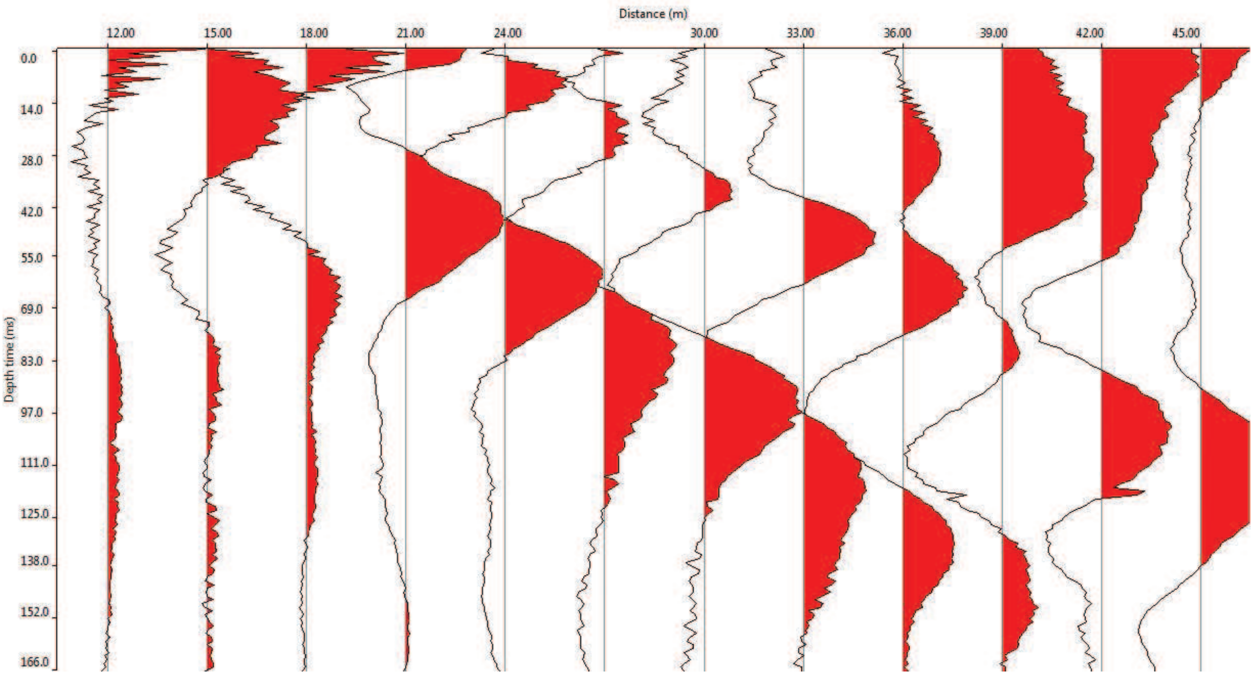

Figure 15. The record of field shot gather.

The fundamental mode corresponding to surface layer (the one which is extending to high frequencies) was picked and come up with the dispersion curve to be inverted/matched using commercial software "*SWAN*" as follows (**Figures 18** and **19**):

Figure 16. The weight drop used to generate vibration in repeat fashion (stacking method).

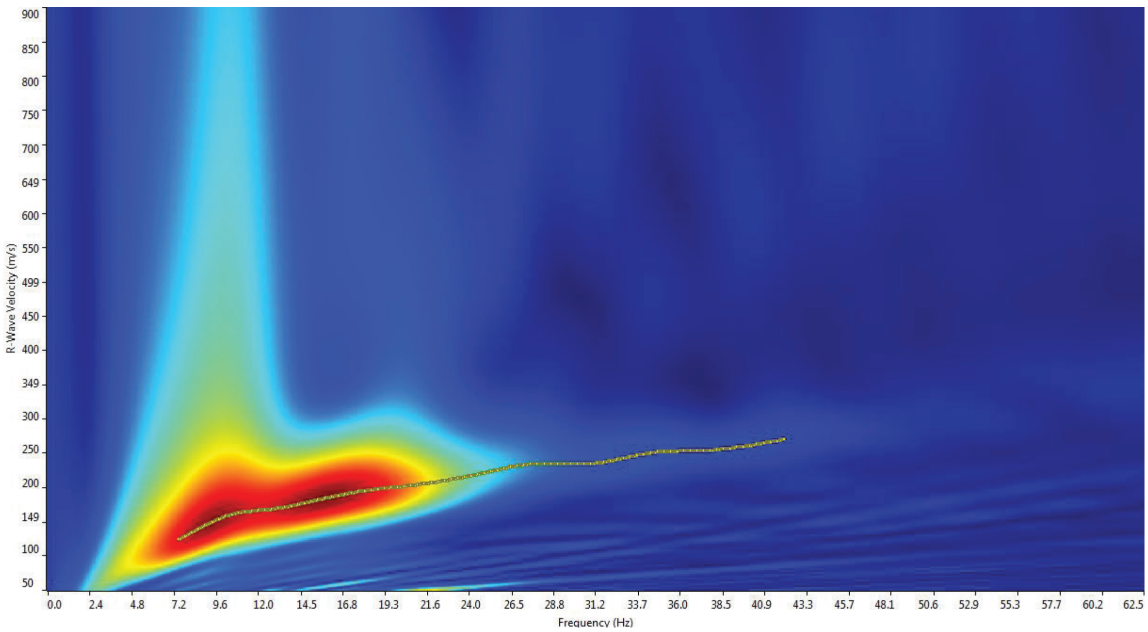

Figure 17. Picking the fundamental mode of surface layer.

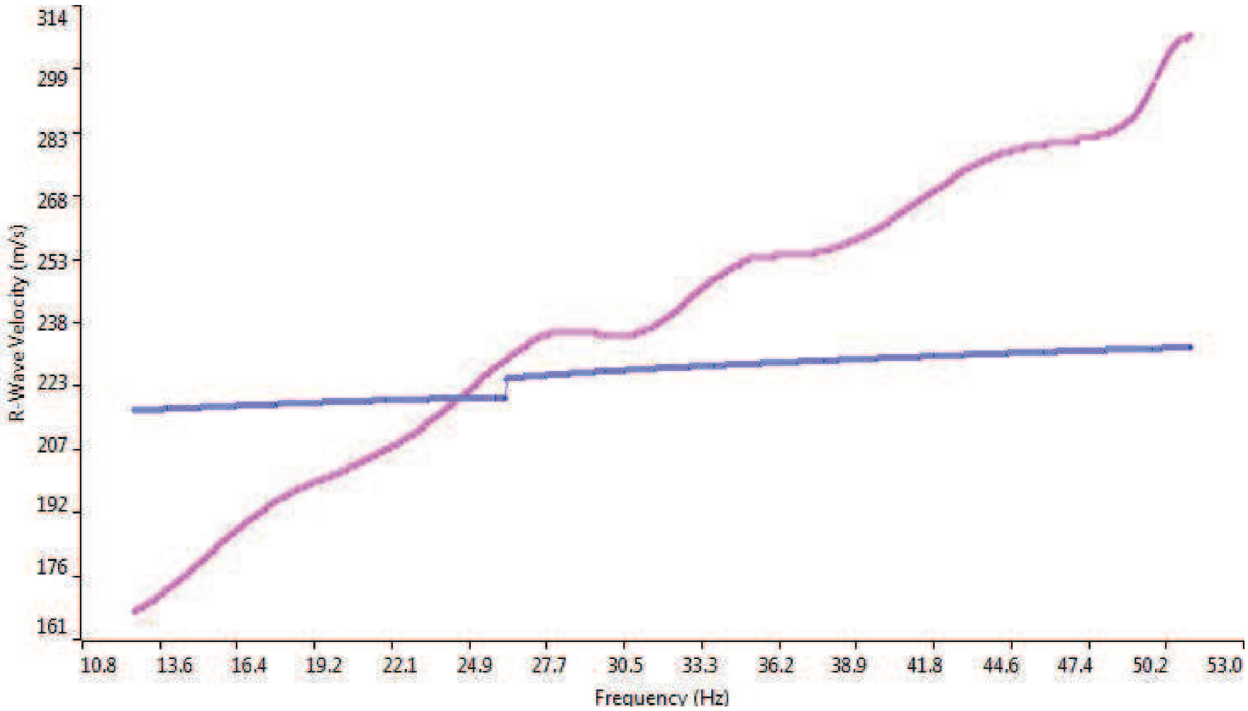

Figure 18. The dispersion curve of surface layer matching.

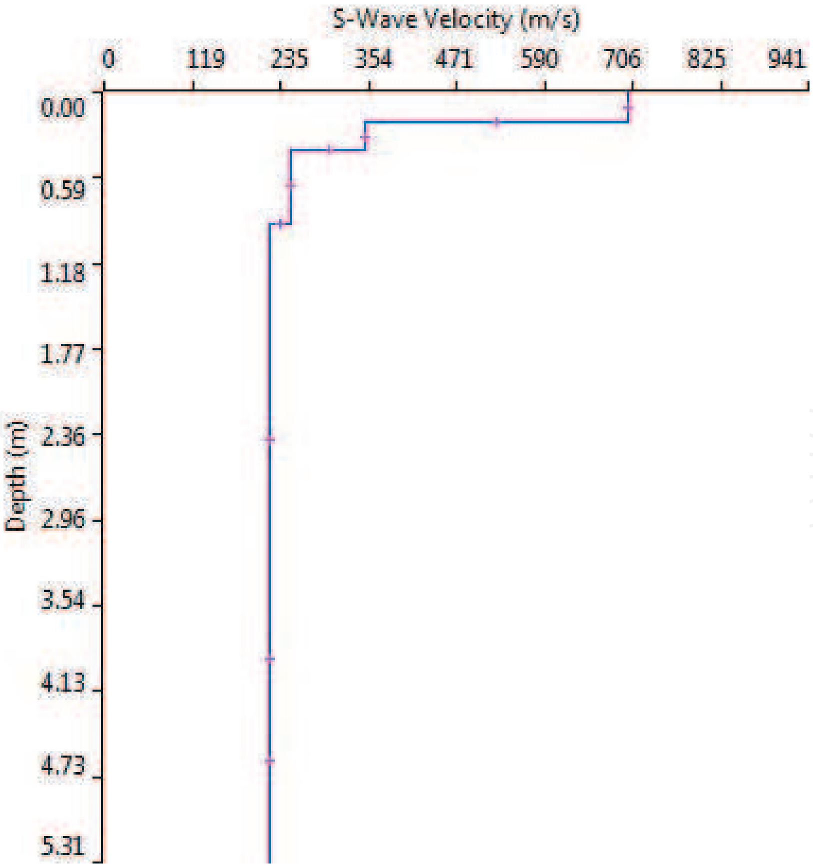

Figure 19. The profile of surface layer of the pavement.

The second branch of spectrum corresponding to the fundamental mode of surface waves from deeper layer was picked as follows (**Figures 20–23**):

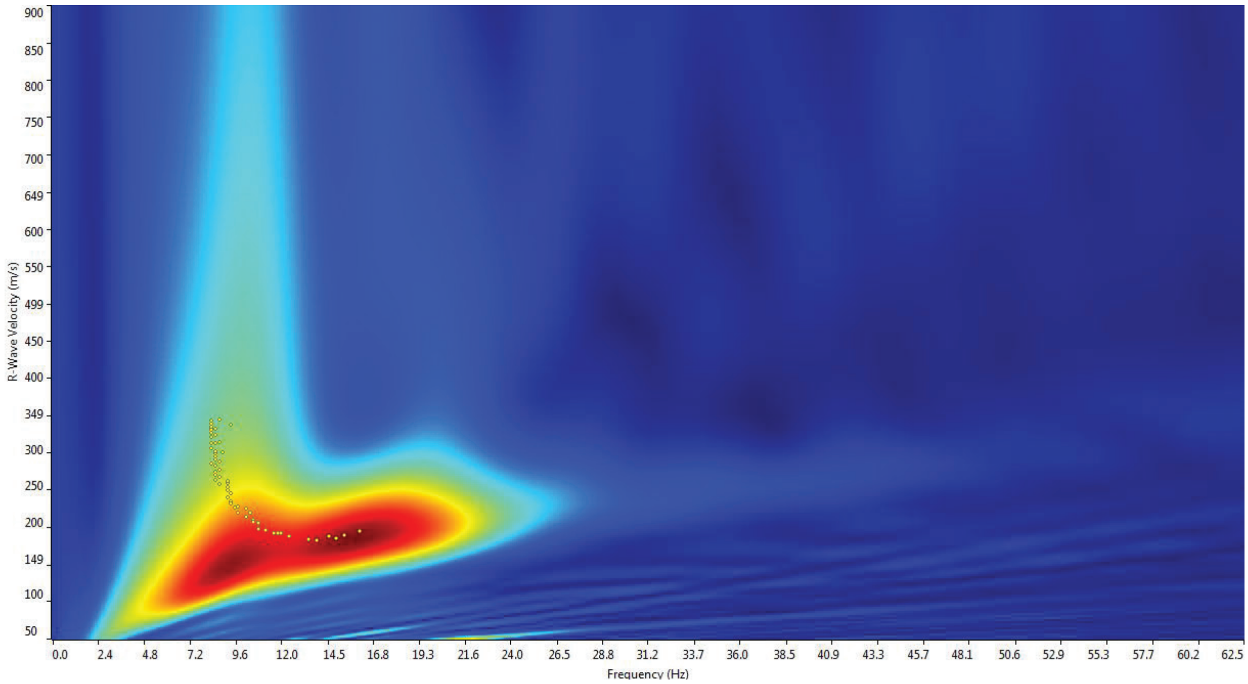

Figure 20. Picking the fundamental mode of surface waves from deeper layer.

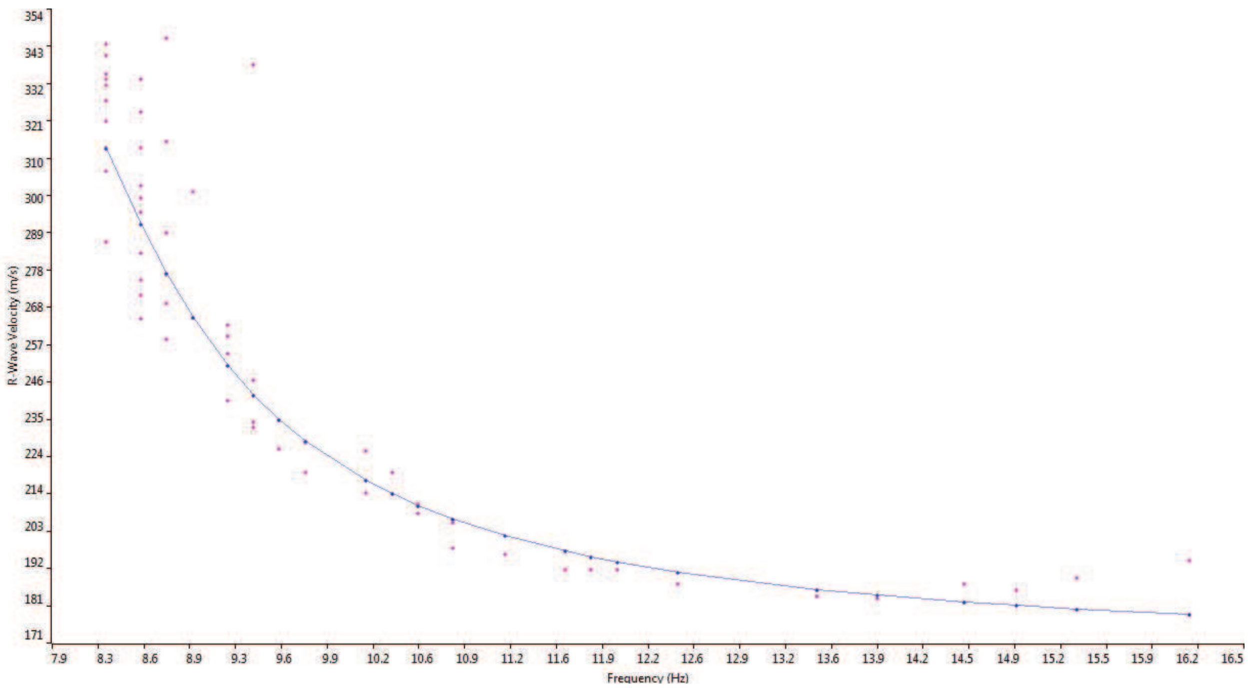

Figure 21. Curve matching of dispersion curve from deeper layer.

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Tables 1 and **2** were combined to come up with **Table 3**, which is the complete shear wave velocity profile of the pavement.

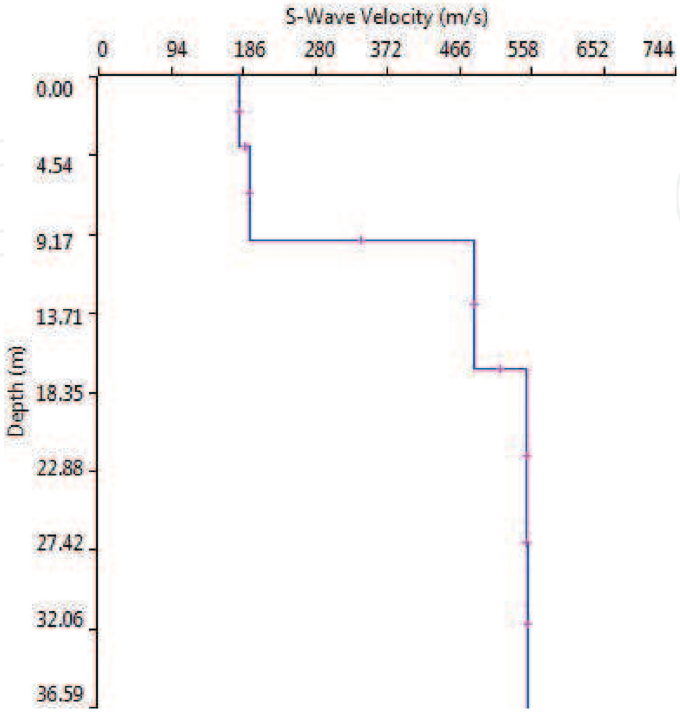

Figure 22. Profile of shear wave velocity with respect to depth of deeper layer (subgrade).

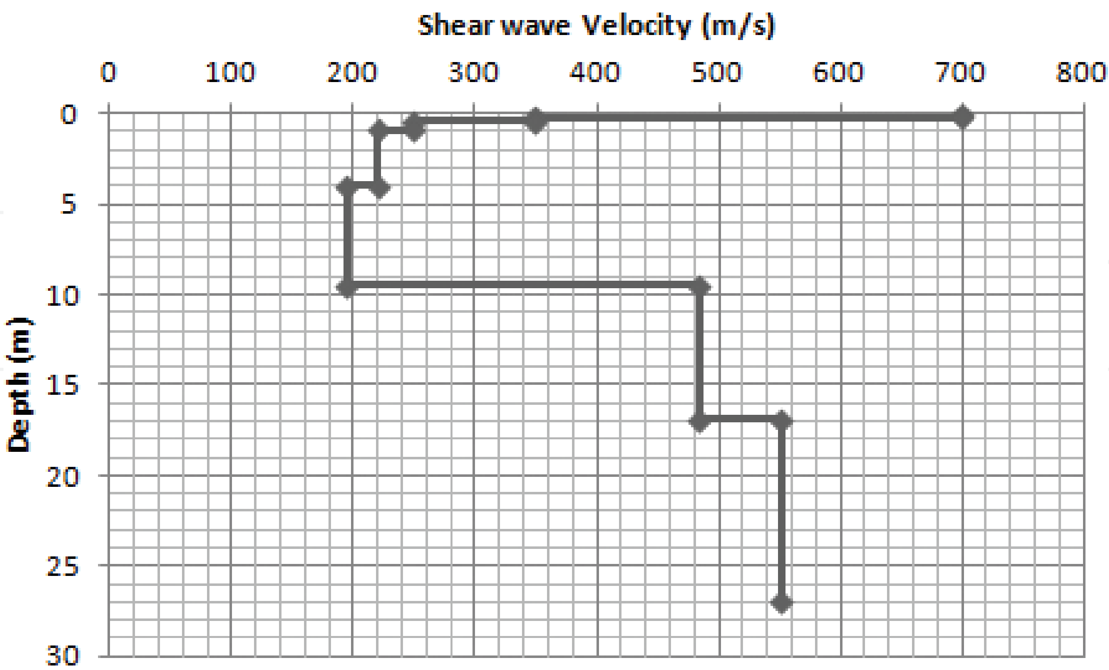

Figure 23. Profile of complete shear wave velocity of the pavement.

Thickness(m)	Depth (m)	Vs (m/s)	Vp (m/s)	Poisson	Density
0.2	0.0	700.0	1399.0	0.33	1.8
0.2	0.2	350.0	699.0	0.33	1.8
0.5	0.4	250.0	500.0	0.33	1.8
3.0	0.9	220.0	440.0	0.33	1.8
	3.9	220.0	440.0	0.33	1.8

Table 1. Results of inversion process of shallow layers.

Thickness (m)	Depth (m)	Vs (m/s)	Vp (m/s)	Poisson	Density
4.0	0.0	182.0	364.0	0.33	1.8
5.5	4.0	195.0	390.0	0.33	1.8
7.4	9.5	484.0	967.0	0.33	1.8
10.1	16.9	551.0	1101.0	0.33	1.8
	27.0	554.0	1107.0	0.33	1.8

Table 2. Results of inversion process of deeper layers.

Thickness (m)	Depth (m)	Vs (m/s)	Vp (m/s)	Poisson	Density (gr/cc)
0.2	0	700	1399	0.33	1.8
0.2	0.2	350	699	0.33	1.8
0.5	0.4	250	500	0.33	1.8
3	0.9	220	440	0.33	1.8
5.5	4	195	390	0.33	1.8
7.4	9.5	484	967	0.33	1.8
10.1	16.9	551	1101	0.33	1.8
	27	554	1107	0.33	1.8

Table 3. Results of combination of processes of shallow and deeper layers.

3. Conclusion

The MASW (Multichannel Analysis of Surface Waves) as nondestructive test for highway engineering was described. A real application to road on North Jakarta was discussed. The measurement was carried out on busy street, but the measurement was success. The results in terms of elastic modulus and thickness of each pavement layer could be used for calculating pavement service life using finite element analysis. The disadvantage of this method is that

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the thickness and shear wave velocity of the layers is along long line, not one point thickness and velocity. In some application such as in construction inspection, it is desired to have the thickness and velocity at one point.

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